

**TITLE OF THE INVENTION**

**METAL COMPLEX-PROTEIN COMPOSITE AND HYDROGENATION  
CATALYST**

**5 BACKGROUND OF THE INVENTION**

**1. Field of the Invention**

The present invention relates to a novel metal complex-protein composite and a novel hydrogenation catalyst.

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**2. Description of the Prior Art**

The inventor of the present invention has proposed metal complex-protein composites of manganese-Schiff base complexes inserted in a cavity of apomyoglobin (apo-Mb) by non-covalent bonding. Here apomyoglobin is obtained by liberating a heme from an oxygen storage protein, myoglobin (Mb). The inventor synthesized, for example, a metal complex-protein composite including a metal complex of manganese with

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20 N,N'-bis(salicylidene)-1,2-phenylenediamine kept in the cavity of apomyoglobin, and reported that such composites were useful for asymmetric oxidation reaction of thioanisole (the Proceedings of the 16<sup>th</sup> Biofunctional

Symposium, '1S1-11 Construction of Artificial Enzyme by Insertion of Metal Complex into Apomyoglobin Cavity' (published in Sep. 2001).

The study of these metal complex-protein composites  
5 has just started, and no useful metal complex-protein composites for hydrogenation reaction have been reported so far.

#### **SUMMARY OF THE INVENTION**

10 The object of the invention is thus to provide a novel metal complex-protein composite. The object of the invention is also to provide a novel hydrogenation catalyst.

The inventor of this invention has developed a novel  
15 metal complex-protein composite as a fruit of intensive studies. The metal complex-protein composite of the present invention includes a protein having a cavity and a metal complex and has a specific structure that the metal complex is received in the cavity of the protein. Here  
20 the metal complex is prepared by complexation of a metal ion, which is selected among the group consisting of rhodium, ruthenium, and palladium, with a ligand. The metal complex-protein composite of the invention

functions as a hydrogenation catalyst of an olefin in water. The metal complex-protein composite is thus effectively applied to hydrogenation of water-soluble substrates and has environmental advantages over organic solvents.

5           Any of diverse methods may be applied to synthesis of the metal complex-protein composite of the invention. Typically there are two applicable methods. One method inserts the metal complex into the cavity of the protein. The other method adds a material of the metal complex (the  
10 material that is changed to the metal complex by a reaction), which is to be received in the cavity of the protein, to a system including the protein having the cavity and synthesizes the metal complex in the system simultaneously with insertion of the metal complex into  
15 the cavity. One concrete procedure of the former method mixes the protein having the cavity with the metal complex at an equivalent ratio of 1 to 0.5 through 100 or preferably at an equivalent ratio of 1 to 1.1 through 2. Preferable solvents for the mixing reaction include mixed solvents  
20 of water and acetone, mixed solvents of water and methanol, mixed solvents of water and dimethylformamide (DMF), mixed solvents of water and dimethyl sulfoxide (DMSO), and water alone. Especially preferable are mixed solvents of water

and acetone and mixed solvents of water and methanol. The mixing temperature is in a range of -10 to 200°C and is preferably in a range of 1 to 4°C. The mixing time is in a range of 0.5 minutes to 24 hours and preferably in a range of 5 to 30 minutes. One concrete procedure of the latter method mixes the protein with the metal ion at an equivalent ratio of 1 to 0.5 through 100 or preferably at an equivalent ratio of 1 to 1.1 through 2. Preferable solvents for the mixing reaction include mixed solvents of water and acetone, mixed solvents of water and methanol, mixed solvents of water and DMF, mixed solvents of water and DMSO, and water alone. Especially preferable are mixed solvents of water and acetone and mixed solvents of water and methanol. The mixing temperature is in a range of -10 to 200°C and is preferably in a range of 1 to 4°C. The mixing time is in a range of 0.5 minutes to 24 hours and preferably in a range of 5 minutes to 1 hour. Another applicable procedure inserts the metal complex into the cavity of the protein carried on a carrier by either of the above two methods. Still another applicable procedure prepares a metal complex-protein composite and replaces the ligand of the metal complex with another ligand.

The protein of the invention may be any one of proteins having either of an amino acid residue that coordinates to the selected metal ion of the metal complex and an amino acid residue that forms a non-covalent bond to the ligand of the metal complex in the cavity thereof, multimers of such proteins, and variants of such proteins. The protein of the invention may otherwise be any one of proteins having the cavity in a heme site by removing a heme from heme-containing proteins, multimers of such proteins, and variants of such proteins. Concrete examples include apomyoglobin, apohemoglobin, apoheme oxygenase, apocatalase, apocytochrome, apoferritin, and their variants. The terminology 'apo' is a prefix representing a protein having a defective cofactor or a defective prosthetic group. Apomyoglobin and apohemoglobin have a defective heme, and apoferritin has a defective iron ion. The variant of the protein preferably has a replacement of an amino acid residue at a position affecting the chemical reaction field of the metal complex received in the cavity of the protein with another amino acid residue suitable for the chemical reaction. The variant of apomyoglobin is, for example, apomyoglobin (polypeptide chain of 153 amino acids) having

replacement of one or plurality of a 64<sup>th</sup> amino acid residue, a 71<sup>st</sup> amino acid residue, a 93<sup>rd</sup> amino acid residue, and a 107<sup>th</sup> amino acid residue. Especially preferable is an apomyoglobin variant having a replacement of a 64<sup>th</sup> histidine (His64) with an amino acid residue smaller than histidine, such as glycine or alanine.

The metal complex of the invention may be any metal complex of the metal ion coordinating to an amino acid residue located in the cavity of the protein or any metal complex of the ligand forming a non-covalent bond to the amino acid residue located in the cavity of the protein. A metal complex including a compound having a phosphino group as the ligand is preferable. Especially preferable is a metal complex including a compound having at least two diphenylphosphino groups as the ligand. One example of the preferable ligand is given as Formula (1):



where R<sup>1</sup> through R<sup>4</sup> represent any of completely identical, partially identical, and completely different substituted and non-substituted hydrocarbons of 1 to 10 carbon atoms and substituted and non-substituted phenyls, and J represents any of substituted and non-substituted hydrocarbons of 1 to 10 carbon atoms and two carbon atoms

included in benzene rings.

The phosphino ligand is not specifically restricted, but may be, for example, any of

bis(diphenylphosphino)methane,

5 bis(diphenylphosphino)ethane,

bis(diphenylphosphino)propane,

bis(diphenylphosphino)butane,

bis(diphenylphosphino)pentane,

bis(diphenylphosphino)hexane,

10 1,2-bis(diphenylphosphino)benzene,

bis(dimethylphosphino)methane,

bis(dimethylphosphino)ethane,

bis(dimethylphosphino)propane,

bis(dimethylphosphino)butane,

15 bis(dimethylphosphino)pentane,

bis(dimethylphosphino)hexane,

1,2-bis(dimethylphosphino)benzene, and

bis(diphenylphosphino) compounds having one or more

hydrogen atoms in the phenyl group displaced by any of

20 substituent groups including alkyl groups, alkoxy groups, nitro groups, carboxyl groups, and halogens. These phosphino ligands are preferably used for the ligand of rhodium complexes and palladium complexes.

The ligand is not restricted to the phosphino ligand but may be a cyclic diene or an aromatic compound that reacts with a metal to produce a metallocene compound. Typical examples of the cyclic diene include

5 cyclopentadiene, cyclooctadiene, and cyclopentadiene and cyclooctadiene derivatives having one or more hydrogen atoms displaced by any of substituent groups including alkyl groups, alkoxy groups, nitro groups, carboxyl groups, and halogens. Typical examples of the aromatic compound  
10 include benzene, naphthalene, and benzene and naphthalene derivatives having one or more hydrogen atoms displaced by any of substituent groups including alkyl groups, alkoxy groups, nitro groups, and carboxyl groups, for example, toluene, xylene, isopropyl benzene, isobutyl  
15 benzene, *o*-, *m*-, and *p*-isopropyltoluene (cymene), and *o*-, *m*-, and *p*-isobutyltoluene. These ligands are preferably used for the ligand of ruthenium complexes.

The hydrogenation catalyst of the invention is composed of the metal complex-protein composite discussed  
20 above and functions to accelerate hydrogenation in water. The amount of the hydrogenation catalyst used depends upon the reaction vessel and the economical efficiency. The molar ratio S/C (where S denotes a reaction substrate and



C denotes the catalyst) is preferably in a range of 10 to 10000 or more specifically in a range of 50 to 5000. The reaction substrate is not specifically restricted but may be any compound having a site to be hydrogenated. The  
5 reaction substrate is preferably water-soluble, since hydrogenation takes place in water. Any aqueous solvent may be used for the solvent of the hydrogenation reaction. Typical examples include water, mixed solvents of water and lower alcohols (for example, methanol and ethanol),  
10 mixed solvents of water and lower ketones (for example, acetone and methyl ethyl ketone), mixed solvents of water and DMF, and mixed solvents of water and DMSO. The reaction temperature is in a range of -10 to 200°C and is preferably in a range of 1 to 50°C. The mixing time is  
15 in a range of 0.5 minutes to 24 hours and is preferably in a range of 5 minutes to 10 hours. This hydrogenation reaction may be in a batchwise operation or in a flow operation.

## 20 BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows Examples 3 through 6; and

Fig. 2 shows syntheses of various metal complex-protein composites.

**EXAMPLES**

Some examples of the invention are discussed below.

In the description below, 'cod', 'dppe', and 'dppb'

5 respectively represent 1,5-cyclooctadiene,

1,2-bis(diphenylphosphino)ethane, and

1,4-bis(diphenylphosphino)butane.

[Example 1]

10 <Synthesis of Rhodium Complex 1>

Rh(I)(cod)(dppe) was synthesized according to the procedure disclosed in a cited reference (Brown, J.M. et al., Journal of Organometallic Chemistry, 1981, vol216, p263-276). The procedure of synthesis mixed [Rh(cod)Cl]<sub>2</sub>

15 (99 mg, 0.2 mmol) with AgBF<sub>4</sub> (80 mg, 0.41 mmol) in acetone in an atmosphere of argon with stirring for three hours and added solid dppe (159 mg, 0.4 mmol) to yield a red solution. The procedure concentrated the red supernatant to 3 ml and added ether (20 ml) to the concentrate to yield  
20 a yellow precipitate. The yellow precipitate was washed with ether and was evaporated. This gave an object compound, Rh(I)(cod)(dppe)·BF<sub>4</sub>. The observed values by ESI-TOF MS (electrospray ionization time-of-flight mass

spectrometry) were  $[\text{Rh}(\text{I})(\text{cod})(\text{dppe})]^+m/z$ : 609.10  
(calculated value: 609.14),  $[\text{Rh}(\text{I})(\text{dppe})(\text{CH}_3\text{OH})]^+m/z$ :  
533.03 (calculated value: 533.38), and  $[\text{Rh}(\text{dppe})]^+m/z$ :  
501.02 (calculated value: 501.04).

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### [Example 2]

#### <Synthesis of Rhodium Complex 2>

$\text{Rh}(\text{I})(\text{cod})(\text{dppb})$  was purchased from Sigma-Aldrich  
Inc. The product name was

10 [1,4-bis(diphenylphosphino)butane]  
(1,5-cyclooctadiene)rhodium tetrafluoroborate.

### [Example 3]

#### <Synthesis of Rhodium Complex-Apomyoglobin Composite 1

15 (see Fig. 1)>

All the operations for the synthesis were performed  
at a temperature of 4°C. Histidine as a 64<sup>th</sup> amino acid  
residue of myoglobin was replaced with alanine according  
to the procedure disclosed in a cited reference (T. Matsui  
20 et al. J. Am. Chem. Soc., 1999, vol121, p9952-9957). The  
variant myoglobin is hereafter referred to as SW H64A Mb.  
The variant myoglobin SW H64A Mb was processed by the  
acid-butanone method described in a cited reference

(F.Ascole et al. Method Enzymol. 1981, vol176, p72-87) and was successively dialyzed with 1 mM, 5 mM, and 10 mM Tris/HCl buffer solutions (pH 7.0) for 2 hours each. This gave apomyoglobin, which is hereafter referred to as

5 apo-H64A Mb. The procedure then mixed apo-H64A Mb with 10 mM Tris/HCl buffer solution (pH 7.0) (385  $\mu$ M, 18 ml), added the acetone solution of the rhodium complex (10 mM, 1.038 ml) obtained in Example 1 with stirring to an equivalent ratio of 1.5 Rh to 1 Mb, and stood still at 4°C

10 for 10 minutes. The resulting mixed solution was dialyzed overnight with 1 liter of 10 mM Bis Tris/HCl buffer solution (pH 6.0). The reconstructed rhodium complex-apomyoglobin composite Rh(dppe)·apo-H64A Mb was purified by gel filtration with G25 and G50 (10 mM Tris/HCl

15 buffer solution (pH7.0)). Here G25 and G50 respectively represent Sephadex G25 Medium and Sephadex G50 Medium (manufactured by Amersham Biosciences K.K.). The resulting composite was identified by ESI-TOF MS, UV-vis analysis, and atomic absorption spectroscopy. The

20 observed value by ESI-TOF MS was 17764.8, which well agreed with the calculated value 17765.4. The absorption maximum wavelength of the composite in UV-vis (ultraviolet-visible spectroscopy) was 259.5 nm, which

was lower than the absorption maximum wavelength of apo-H64A Mb (280 nm). The concentration of Rh was determined to be 1.77 mM by atomic absorption spectroscopy.

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[Example 4]

<Synthesis of Rhodium Complex-Apomyoglobin Composite 2  
(see Fig. 1)>

A rhodium complex-apomyoglobin composite

10 Rh(dppe)·apo-Mb was obtained according to the same  
procedure as that of Example 3, except that myoglobin was  
not replaced. The observed value of the resulting  
composite by ESI-TOF MS was 17829.9, which well agreed with  
the calculated value 17831.1. The absorption maximum  
15 wavelength of the composite in UV-vis analysis was 274.5  
nm, which was lower than the absorption maximum wavelength  
of apo-Mb (280 nm). The concentration of Rh was determined  
to be 1.13 mM by atomic absorption spectroscopy.

20 [Example 5]

<Synthesis of Rhodium Complex-Apomyoglobin Composite 3  
(see Fig. 1)>

A rhodium complex-apomyoglobin composite

Rh(dppb)·apo-Mb was obtained according to the same procedure as that of Example 4, except that the rhodium complex obtained in Example 2 was used instead of the rhodium complex obtained in Example 1. The observed value  
5 of the resulting composite by ESI-TOF MS was 17859.8, which well agreed with the calculated value 17859.2.

[Example 6]

<Synthesis of Rhodium Complex-Apomyoglobin Composite 4  
10 (see Fig. 1)>

Another method was applied to synthesize a rhodium complex-apomyoglobin composite. This method synthesizes a rhodium complex in situ in the presence of apomyoglobin to obtain the rhodium complex-apomyoglobin composite.  
15 The procedure added an acetone solution of [Rh(cod)Cl]<sub>2</sub> (2 mM, 2 µl) (at an equivalent ratio of 2 Rh to 1 Mb) and an acetone solution of dppe (2 mM, 4 µl) to a 5 mM ammonium acetate solution of apo-H64D Mb (having a replacement of a 64<sup>th</sup> histidine with aspartic acid) (20 µM, 200 µl) and  
20 stood the mixed solution still at 4°C for 1 hour. The observed value of the resulting composite by ESI-TOF MS was 17808.0, which well agreed with the calculated value 17809.1 of the composite of cod-free Rh(I)(dppe) and

apo-H64D Mb.

[Example 7]

<Hydrogenation Reaction of Olefin 1>

5           The rhodium complex-apomyoglobin composite  
Rh(dppe)·apo-H64A Mb obtained in Example 3 was used for  
hydrogenation reaction of acrylic acid. The  
concentration of Rh of the purified composite was  
determined by atomic absorption spectroscopy. Acrylic  
10 acid went through a hydrogenation reaction in 50 mM  
phosphate buffer (pD 7.0) for 5 hours under the conditions  
of [Rh]/[substrate] = 1/100, a temperature of 35°C, and a  
hydrogen pressure of 5 atm. Here pD represents  $-\log_{10}[D+]$   
(D is deuterium). The procedure placed an aqueous  
15 solution of the rhodium complex-apomyoglobin composite  
(0.5 mM, 1 ml, 0.5  $\mu$ mol) in an auto clave, added an aqueous  
solution of acrylic acid (50 mM, 1 ml, 50  $\mu$ mol) to the  
aqueous solution of the rhodium complex-apomyoglobin  
composite, and replaced the atmosphere in the auto clave  
20 with gaseous hydrogen for the hydrogenation reaction under  
the above conditions. This hydrogenation reaction  
changed acrylic acid to propionic acid. The turnover  
number measured by  $^1\text{H-NMR}$  was  $0.68 \text{ h}^{-1}$ .

## [Example 8]

## &lt;Hydrogenation Reaction of Olefin 2&gt;

Acrylamide was subjected to hydrogenation reaction  
5 with the rhodium complex-apomyoglobin composite  
Rh(dppe)·apo-Mb obtained in Example 4, according to the  
same procedure as that of Example 7. This hydrogenation  
reaction changed acrylamide to propionamide. The  
turnover number measured by  $^1\text{H}$ -NMR was  $0.60\text{ h}^{-1}$ .

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## [Example 9]

Various metal complex-protein composites were  
synthesized according to reaction formulae shown in Figs.  
15 2(a) through 2(d). Apomyoglobin used here was apo-H64D  
Mb. The observed values of the resulting metal  
complex-protein composites by ESI-TOF MS were also shown  
in Fig. 2. Concrete procedures of the syntheses were  
discussed below.

20 Fig. 2(a): The procedure of the synthesis mixed an  
apo-H64D solution ( $212\text{ }\mu\text{M}$ ,  $14\text{ ml}$ ) with an acetone solution  
of  $[\text{Rh}(\text{cod})\text{Cl}]_2$  ( $10\text{ mM}$ ,  $150\text{ }\mu\text{l}$ ) and stood the mixed solution  
still at  $4^\circ\text{C}$  for 10 minutes. The mixed solution was



dialyzed overnight with 10 mM Bis Tris/HCl buffer solution (pH 6.0). The reconstructed rhodium complex-apomyoglobin composite Rh(cod)·apo-H64D Mb was purified by gel filtration with G25 and G50. The observed value of the composite by ESI-TOF MS was 17516.6, which well agreed with the calculated value 17519.1.

Fig. 2(b): A palladium complex-apomyoglobin composite Pd(dppe)·apo-H64D Mb was obtained according to the same procedure as that of Fig. 2(a), except that a Pd(dppe)DMF solution prepared by mixing Pd(dppe)Cl<sub>2</sub> and AgBF<sub>4</sub> in DMF and liberating Cl was used as the metal complex solution. The observed value of the composite by ESI-TOF MS was 17814.8, which well agreed with the calculated value 17812.0.

Fig. 2(c): A methanol solution of dichloro(*p*-cymene)ruthenium dimer (2 equivalent weight) was added to a 5 mM ammonium acetate solution of apo-H64D Mb (20 μM, 200 μl), and the mixed solution was stood still at 4°C for 1 hour. The observed value of the composite by ESI-TOF MS was 17544.3, which well agreed with the calculated value 17543.4.

Fig. 2(d): A ruthenium complex-apomyoglobin composite was obtained according to the same procedure as

that of Fig. 2(c), except that a mixture of a methanol solution of dichloro(*p*-cymene)ruthenium dimer (10 mM, 100  $\mu$ l) and a methanol solution of 1,8-diaminonaphthalene (20 mM, 100  $\mu$ l) mixed at room temperature, stirred for 1  
5 minute, and stood still overnight at room temperature was used as the metal complex solution. The observed value of the composite by ESI-TOF MS was 17700.9, which well agreed with the calculated value 17699.6.

A composite of apocytochrome c was discussed as  
10 another example. The procedure mixed apocytochrome c with ruthenium chloride (*p*-cymene)(4-methyl-1,2-benzenediamine) at a rate of 1 to 1 or 1 to 2 and placed the mixture on ice for more than 10 minutes. The mixture was dialyzed with ammonium  
15 acetate buffer (5 mM, pH 6.8, 4°C) for 12 hours and was passed through a G50 gel filtration column equilibrated by ammonium acetate buffer (5 mM, pH 6.8 4°C) for purification. This gave a ruthenium  
(*p*-cymene)(4-methyl-1,2-benzenediamine)-apocytochrome  
20 c composite. The observed value of the composite by ESI-TOF MS was 12097.1, which well agreed with the calculated value 12098.